1.1. The Cockcroft Institute Wakefields Interest Group

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1.1.1. Introduction

The Cockcroft Institute is a newly created international centre for Accelerator Science and Technology in the UK. It is a joint venture between the Universities of Lancaster, Liverpool and Manchester, and the Science and Technology Facilities Council. The Cockcroft Institute has a large expertise base in Wakefields and Impedances which is linked through the Cockcroft Institute Wakefields Interest Group. Members of this group have experience in wakefields in linear colliders, ring colliders, light sources as well as generic fundamental research and focus on a wide range of specialist areas. In this article we summarize the work performed in this important field of research at the Cockcroft Institute.

1.1.2. Wakefields from Start to End in Linear Colliders

The Cockcroft institute has a large amount of expertise in wakefields and impedances and their effects in e+/e- linear colliders. Work has been performed on wakefields from start to end on the proposed ILC and CLIC colliders, including positron sources, damping rings, main linac and the collimators and crab cavities of the beam delivery system. In the following sub-sections we will look at the work performed in each of these key areas.

1.1.2.1. Wakefields in the ILC Positron Source Undulator Line

The ILC positron source relies on a long (~200 m) helical undulator producing ~MeV photons when the main electron beam, at 150 GeV, passes through it. To achieve the high on-axis magnetic fields the magnet has a cylindrical bore with a diameter of ~6 mm. The magnet is superconducting and operates at ~ 4 K [1]. The undulator is built in ~4 m long modules. In the current design, the undulator module has tapered transitions between the cold bore and room temperature connections. These are necessary to

accommodate the bellows and sliding joints needed to handle contractions during cool-down of the magnet. The undulator line consists of a FODO lattice with three undulator modules, ~4 m in length, between quadrupoles. In order to achieve the required vacuum their must be photon collimators [2]. These are placed in the gaps between undulator modules where there are no quads. They are axially symmetric, have a minimum (full) aperture of 4.4 mm and taper angle of 100 mrad.

The effects of resistive wall and geometric wakefields of the undulator beam-tube, cold to warm transitions and the photon collimators on the beam have been assessed for the undulator line [3,4,5,6]. As the main electron beam passes through the undulator line before reaching the interaction point it is important to ensure that any disruptions are acceptable.

For the resistive wall wakefields, DC, AC, and ASE conductivity models of different materials were considered for Gaussian and non-Gaussian charge distributions. The studies indicated that a stainless steel tube should not be used, unless it was coated with a suitable material. Aluminium, gold or copper would all be suitable. It was found that the total energy lost and increase in energy spread of the beam for a copper tube at 77 K was ~ 0.15 MeV m^{-1} and 10^{-5} m^{-1}, respectively. For this tube a transverse momentum kick of ~0.26 eV μm^{-1} m^{-1} was calculated and the increase in emittance associated with such a kick is negligible. Further studies by the ILC-Low Emittance Transport working group have confirmed the emittance increase is currently acceptable [7]. The heating of the undulator due to image currents is expected to be 0.081 W m^{-1}, in the worst case.

The effects of the surface roughness on the energy spread indicated that an extremely smooth vessel, with surface roughness features <300 nm should be used to keep the induced energy spread below 10% of the nominal ILC value. A smooth copper vessel, with surface roughness ~100 nm and the required dimensions is available from industry today [8].

The geometric wakefields of the undulator transitions and photon collimators were assessed using ECHO2-D [9] and analytic formula [10]. For the cylindrically symmetric tapered elements a good agreement between the two methods was found. ECHO was used to assess the wakefields of the bellows. The emittance increase due to misalignments of these elements was calculated. The misalignment of each element was randomly chosen from a Gaussian distribution for different rms values, truncated at ±300 μm (to reflect accurate surveying of the components). For an rms value of 300 μm the average vertical emittance increase of 1 000 different undulator lines was 2.7%.

All calculations, so far performed, on the wakefield affects on the electron beam of the ILC positron source undulator system have been demonstrated to be acceptable. It is planned that further work will continue to update the calculations with better

conductivity models of 4 K vessels, and account for the latest ILC beam parameters and component designs. There is also plenty of opportunity to optimise the design. For example, the taper angles, number of photon collimators and their aperture all have potential to be changed if further studies indicate a need.

1.1.2.2. Effect of Beta Function Variation on Multi-Bunch Instability in Damping Rings

Instability of bunches that are coupled by resistive wall wake fields in a storage ring is a well-known phenomenon. The instability is generally understood in terms of a model that has been widely used for many years [11]. In order to obtain a solution analytically, this model has to assume that the beta function is a constant around the ring. The resulting solution of the equations of motion gives the growth rates of the bunch amplitudes. During the design of a storage ring, this information can be used to specify the feedback system needed to control the growth.

In linear collider damping rings [1], the large number of bunches and narrow beam pipe (for example, in the damping wiggler) lead to coupled-bunch growth rates that approach the limits of modern feedback systems. A highly accurate estimate of the growth rates is needed to provide sufficient confidence in the specifications for the feedback system, and this motivates a re-examination of some of the underlying assumptions in the conventional model. Assumptions that may need to be addressed include: use of constant beta function; uniformity of the fill pattern; uniformity of the beam pipe; and linearity of the dynamics.

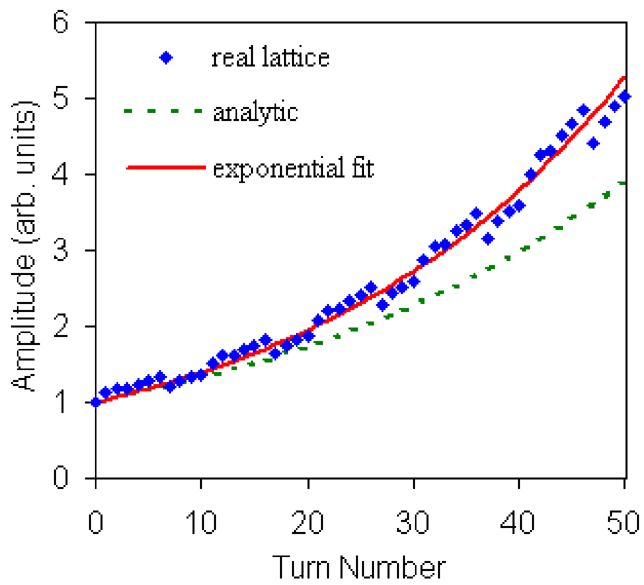

Figure 1: Time domain simulation in a design for the ILC damping ring, for bunches arranged in the mode with maximum growth rate. The blue points show the amplitude of one of the bunches.

Here, we consider the impact of variation of the beta function on coupled-bunch growth rates in the damping rings of the International Linear Collider. As it is no longer possible to find an analytic solution to the equations of motion when variations in the beta function are included in the model, time domain simulations have to be performed to find the transverse motion of the bunches. Figure 1 shows how the amplitude of one of the bunches stored in the ring grows with the number of turns around the ring. Details of the method used are given in [12]. With beta function assumed constant, the growth time is calculated to be around 37 turns; the time-domain simulations, using the real beta function in the lattice, predict a growth time of 30 turns. Given that a state-of-the-art feedback system would be able to provide a damping time of around 20 turns, the more accurate model (using the real beta function) indicates a much narrower margin; however, it should still be possible to control the instability using a feedback system.

Further topics likely to be important for the study of long range wake fields in linear collider damping rings include: the effects of thin coatings (that may be used to improve vacuum and suppress electron cloud); and the effects of uneven fill patterns. Related to uneven fill patterns are effects associated with transients that may arise during the extraction and injection process. For example, typically undamped bunches would be injected into the damping rings before all the damped bunches are extracted. Long-range wake fields may couple jitter on the injected bunches to the damped bunches, leading to unpredictable bunch-to-bunch jitter on the extracted beam. Given the sensitivity of a linear collider to beam stability, a thorough and detailed understanding of such effects is necessary, in order to optimise the design.

1.1.2.3. Wakefields in the ILC and X-FEL Main Linacs

The modes excited by the accelerated beam in the main linacs of the XFEL facility in DESY and the proposed ILC [1] will give rise to wake-fields which disturb the progress of the bunches and in the worst case scenario can give cause a BBU (Beam Break Up) instability. We are studying these wake-fields with a view to characterising their influence on beam dynamics with realistic fabrication errors included. In order to facilitate an understanding of modes trapped in accelerating cavities within multiple modules in particular, we have applied a global scattering matrix technique [13] which enables the modes of the structure to be rapidly determined. This methodology is being applied to both understand the electromagnetic field in the modules at FLASH and those in the ILC. Indeed, as part of a collaboration between four laboratories (SLAC, DESY, FNAL, and Cockcroft) and two Universities (Manchester and Rostock) we are also actively involved in an experimental accelerator beam studies program at FLASH with a view to developing beam position monitors from the signal

generated from the higher order dipole modes (HOM) radiated to the HOM couplers. To date the HOM beam position monitors developed for this purpose have indicated a beam alignment of better than 5μm [14]. Further studies are ongoing developing methods to characterise the cavity and sub-cavity misalignment from similar measurements of the dipole radiation. In addition to the work on the TESLA-style cavities, we are also engaged in studying the mode properties of the new high gradient designs proposed by KEK in the form of a low loss Ichiro cavity and by Cornell University as a re-entrant shape. The modes in these cavities have been analysed for up to 6 bands using several computer codes in which we take advantage of parallel processing and their impact on the beam dynamics has been ascertained by tracking the beam through the complete linac [15, 16]. Detailed simulations have been conducted on the damping requirement of the HOM couplers and modes with particularly damaging transverse kick factors have been found.

We note that this research has resulted in two students graduating at the University of Manchester with MSc theses in the area of HOM wake-fields in both the main linacs [17] and crab cavities [18] of the ILC.

1.1.2.4. Collimator Wakefields

The collimator wakefield work at the Cockcroft Institute is centred on advancing the state of the art in design procedures through comparison of 3D EM simulations, experimental measurements produced in collaboration with partners in the UK and at SLAC, and analytical theory, and to enable higher order modes to be incorporated into tracking codes such as MERLIN and PLACET.

The collimator apertures in the ILC beam delivery system are required to be small, with the betatron spoiler apertures expected to be of the order of 1 mm [1]. This tight collimation of the beam halo allows synchrotron radiation emitted in the strongly focussing final quadrupoles to pass cleanly through the interaction region, thus minimising the detector background. This constraint combined with the low emittance of the ILC beam means that the physical aperture of the collimators is very narrow, giving rise to large wakefield effects. These may perturb the beam, distort the bunch shape, increase the emittance and thus decrease the luminosity. It is important to study such effects to ascertain whether they pose a problem.

Collimator wakefields differ from cavity wakefields as a collimator is not naturally resonant, and the expansion of wakefields in frequency space is therefore less simple. This lack of high Q resonances also means that wakes will not persist and we can concentrate on the study of short range intra-bunch wake effects rather than the long range inter-bunch ones. Also we study

only transverse wakes, ignoring any potentially disruptive effects of longitudinal wakes on the particle energies.

The kick factor κ is generally defined [11] by the relation between the displacement and deflection

$$\Delta y' = \frac{N r_e \kappa \Delta y}{\gamma} \qquad (1)$$

This is a simplification in two respects: firstly it assumes that the wakefield is a dipole, and that higher terms can be ignored, secondly it refers to the displacement and deflection of the bunch as a whole and does not describe the different fields experienced by different particles.

Initially MAFIA was used, and through comparison we were able to prove the validity of fields calculated with GdfidL[19]. This provides a platform on which we are able to run simulations on a much larger scale, principally due to features such as a moving mesh solver and parallel architecture[20]. Our principal concern was the transverse geometric kick, and prototype collimators were simulated that were tested on the 28.5 GeV beam at SLAC, results are in good agreement. [21]

In addition to the transverse geometric kick, we also developed prototypes to investigate resistive wall wake, and surface roughness.

The measurements for all of these have been compared with analytical estimates of their values.

The MERLIN C++ library provides a way of simulating effects on individual particles. In its standard form it only provides dipole transverse wakes, and it furthermore assumes that any transverse deflection is radial. We have adapted this to more general transverse fields and angular modes of arbitrary order [22]. We are still restricted to cases of axial symmetry, and represent a rectangular collimator by a circular one of diameter equal to the smaller rectangular dimension: this is inexact but enables us to consider order of magnitude effects.

In these simulations we use the formula for the geometric wake of a collimator tapering from radius a to radius b given in [23]

$$W_m^{\perp}(z) = 2\left(\frac{1}{a^{2m}} - \frac{1}{b^{2m}} \right) \exp\left(- \frac{m\pi z}{a} \right) \Theta(z) \qquad (2)$$

but any other formula can readily be implemented in the code.

Simulation studies of a single collimator confirm that if the beam displacement is small compared to the gap size, the dipole mode is adequate. However larger offsets need more modes for a full description [24]. The bunch also shows considerable distortion: the head is unaffected, but the effect increases down the bunch length, and then lessens again in the far tail.

Studies were then performed on the ILC BDS [25], looking at the loss in luminosity as a function of the beam offset at the exit of the Linac.

Luminosity was taken from the emittance and bunch-bunch interactions were not considered. Effects are small for reasonable displacements, and the effect of higher order modes only becomes significant at unrealistically large displacements. Studies were performed for resistive wake effects and give reassuringly similar results. Further studies with different collimator shapes and materials are planned to confirm them. A similar study using the PLACET program [26] was conducted revealing qualitatively similar results. This does consider rectangular cavities and the beam-beam effect on luminosity, but does not include higher angular modes.

1.1.2.5. Calculations of Impedances and Wakefields in Crab Cavities

The current ILC [1] design requires a crab cavity [27] in order to rotate the beams prior to collision. It is necessary for these cavities to be close to the final focus in a region with a high beta function. Due to this, the crab cavity wakefields (particularly in the transverse plane) can have very large detrimental effects on machine luminosity. For dipole-mode cavities in general, the fundamental monopole mode is an unwanted mode and due to the relatively small beam pipe diameter, this mode becomes trapped in the cavity. This mode, referred to as the lower order mode (LOM) requires damping (QL typically $<10^4$ for ILC) to avoid excessive fields in the cavity and couplers.

The ILC crab cavity is a 9-cell superconducting RF (SRF) cavity with the fundamental dipole mode being resonant at 3.9 GHz [28]. The finite difference code MAFIA was used to calculate all the dipole modes up to 18 GHz and monopole higher order modes (HOM) up to 16 GHz. The results of these simulations have been used to specify the required damping in order to stop collective effects deflecting the beam by more than $\sigma/4$ at the IP [29]. The MAFIA simulations have also been used in conjunction with a diffractive technique to calculate the single bunch wakefields. These calculations were verified by simulating the cavity using the code ECHO2D, and are shown in Figure 2.

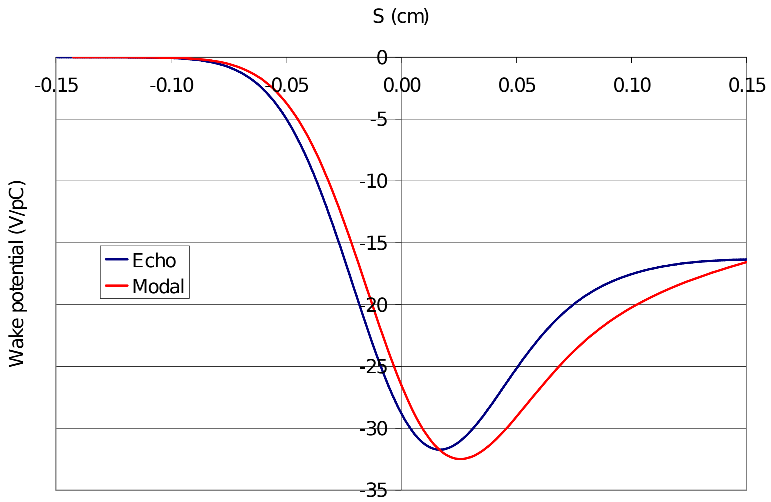

Figure 2: Longitudinal short range wakefields, comparing ECHO 2D and modal/diffractive calculation.

Having calculated the higher and lower modes of the cavity and the delta wake at short range, the effect of the wakefields were calculated in the particle tracking code PLACET as well as using analytical techniques. The output from PLACET was also used with GUINEA-PIG to calculate the loss in luminosity due to the wakefields.

After verifying the design in simulations, a prototype of the crab cavity with its couplers was constructed out of aluminium and copper. This prototype has been used to verify the simulation results by measuring the loss factors, kick factors and external Q factors of the dominant cavity modes. The field structure of the first monopole and dipole passbands were studied using bead-pull techniques, utilising metal beads, dielectric beads and metal needles. The dipole modes up to 13 GHz were studied using a frequency domain reflectrometry technique [30], shown in Figure 3, where a wire is stretched along the beam pipe and the wire transmission is measured as a function of frequency. This method provides a measurement of the transverse impedance and hence the kick factor and resonant frequency of the modes can be evaluated. Finally the external Q factor of the most dominant modes were measured using a series of reflection and transmission measurements at the couplers.

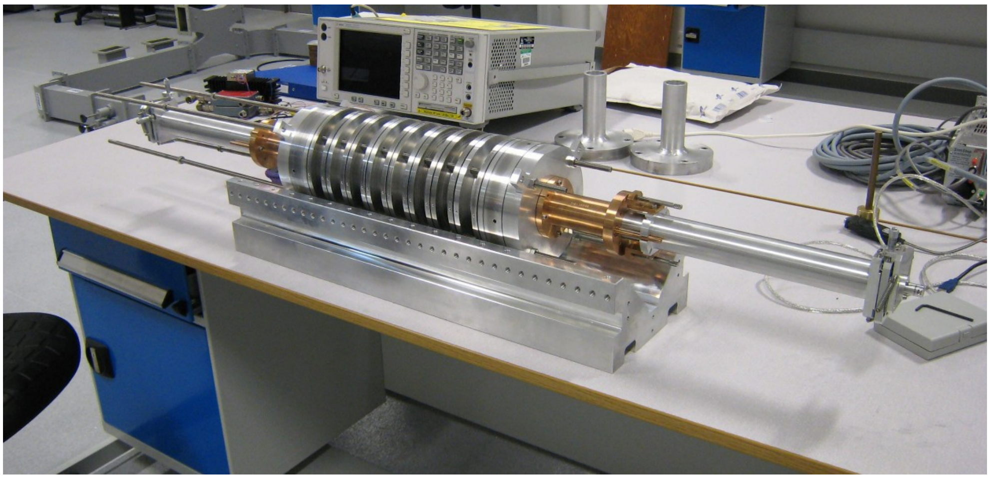

Figure 3: Wire test experimental set-up

The Cockcroft Institute has now commenced a program of research looking into the design of a crab cavity system for CLIC, and also on the development of a crab cavity system as an upgrade option for LHC in collaboration with CERN and US-LARP.

1.1.3. The Mathematical Physics Group

The Mathematical Physics Group at Lancaster University is applying methods of differential geometry and the electrodynamics of continuous media to fundamental problems in laser-plasma interactions and electron beam dynamics in the vacuum. The research is motivated by contemporary challenges that arise in the control of beam stability in the presence of coherent electromagnetic radiation in intense light-sources and future laser wake-field accelerators.

A principle aim of their work is to explore the motion of large collections of rapidly accelerating charged particles in small bunches moving at ultra-relativistic energies in the laboratory (see, for example, [31] on the behaviour of relativistic spinning particles in electromagnetic fields). They have developed a covariant perturbation theory [32] that offers a new mathematical approach in regimes where a charged fluid description provides insights to collective effects analogous to turbulent mixing in fluid dynamics [33]. This work is being developed in a number of directions including the influence on the bunches of boundary effects of various kinds, the influence of radiation reaction and the inclusion of statistical fluctuations via a new formulation of the relativistic Maxwell-Vlasov equation.

Wake-fields arise in many of their studies. Particular programs include radiation properties in straight guides with slowly varying cross-sections and guides with fixed cross sections but slowly varying curvature.

1.1.4. Large Hadron Collider

We maintain a significant involvement with activities at CERN in research on the RF properties of various components of the LHC and in participating in beam commissioning. In particular, we have conducted research in areas related to impedance measurement and calculation.

In the first area, the FP420 collaboration is assessing the feasibility of detecting protons outgoing from the LHC beams collision, that have lost less than 2% of their longitudinal momentum [34]. We launched a campaign of studies to verify the different aspects of the FP420 impedance. Analytical calculations and numerical simulations assess the longitudinal and transverse impedance values. Laboratory measurements on the available FP420 station prototypes have been used to benchmark the simulations. The relevant upper frequency limit is assessed by the nominal LHC rms beam bunch length, $\sigma_z = 0.25$ ns. This permits us to limit our study up to a frequency of 3 GHz. The majority of the studies are based on the stretched wire method for evaluating the longitudinal coupling impedance through the measurement of the scattering parameters of the device under test [35]. The laboratory setup at the Cockcroft Institute comprises a sophisticated mechanical system equipped with micrometers, to stretch, move and monitor the relative position of the wire. The impact of the impedance on the overall impedance budget of the LHC has been verified to be acceptably small.

The second area of research is on the LHC ATLAS, Roman Pot-like detectors [36]. The impact of the insertion of these detectors on the LHC beam coupling impedance is under investigation. In the laboratory, the stretched wire method has been applied to an ATLAS Roman Pot prototype while setting the pots at different locations from the nominal operation positions. A second set of measurements has been taken after mounting on the pots walls ferrite tiles with the aim of absorbing the electromagnetic power at the observed resonances. Results are shown in Fig. 4 in terms real part of the longitudinal impedance with and without damping. This research is ongoing with an aim to add further ferrite dampers in the roman pots to minimize the impact on the beam dynamics.

(a) **(b**

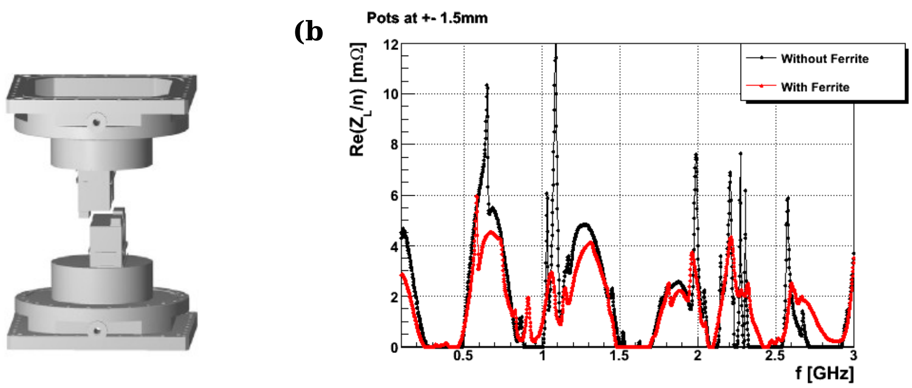

Figure 4: (a) Roman pot detector and (b) the real part of longitudinal impedance of as measured before and after inserting absorbing ferrite tiles into the pot.

Finally, the third area of research is concerned with verifiying the prediction of the resistive wall transverse beam impedance down to frequencies around the first unstable betatron line (8 kHz) of the LHC. The Cockcroft Institute are participating in a series of laboratory measurements at CERN with the aim of benchmarking analytical predictions and numerical simulations of the resistive wall transverse impedance. At such low frequencies, in the presence of resistive materials with thickness larger than the distance between the beam and the material itself, and below a critical frequency that is related also to the material skin depth, recent theories [37,38] diverge from classical models. The aim of the experiment at CERN is to validate the predicted divergence with a method based on the measurement of the variation of a probe coil inductance [39] in the presence of three set-ups: sample graphite plates, stand-alone LHC collimator jaws and a full LHC collimator assembly. Preliminary results validate the theory in all the relevant frequency range and will be presented at the forthcoming EPAC08 conference [40].

1.1.5. Light Sources

Light sources driven by electron accelerators utilise either undulators or wigglers, and there is usually a demand to minimise the magnet (and therefore vacuum) gap in these devices both to maximise the magnetic field that is technologically available, and thereby to minimise the electron beam energy required for a particular wavelength output. This is particularly true for linacs driving free-electron lasers (FELs), where a reduction in magnet gap from, say, 10 mm to 5 mm can save up to 30% of the linac [41]. Whether this is practicable or not is often down to the resistive-wall wakes that drive energy spread growth in the short bunches and heating of the enclosing vacuum vessel, problems that are exacerbated if those bunches are very short (e.g. sub-picosecond), as is demanded for FEL and short-pulse photon output. The EuroFEL collaboration for future light sources [42] has been examining wakefield limitations for such sources, in which the Cockcroft Institute has been involved.

Some wiggler sources desire very high fields that are more conveniently created using superconducting magnets, and a cold beam vessel allows the magnet gap to be minimised. The anomalous skin effect (ASE) however changes the conductivity at these low temperatures [43], and the image current heating of these cold vessels can be markedly larger; in high-repetition-rate systems such as an energy recovery linac this heating can dominate the total heat load and make cooling difficult, so it is important to estimate the effect of the ASE to determine the choice of vacuum

vessel material and cooling. For example, the 4GLS proposal [44] has a target of 1.3 GHz, 77 pC bunches in the ERL section with a length down to 100 fs. Figure 5 shows the relative heat loads of the ERL compared to the lower repetition rate XUV line, calculated using an image-current heating approach; the resistive wakefield loss approach gives comparable results [45].

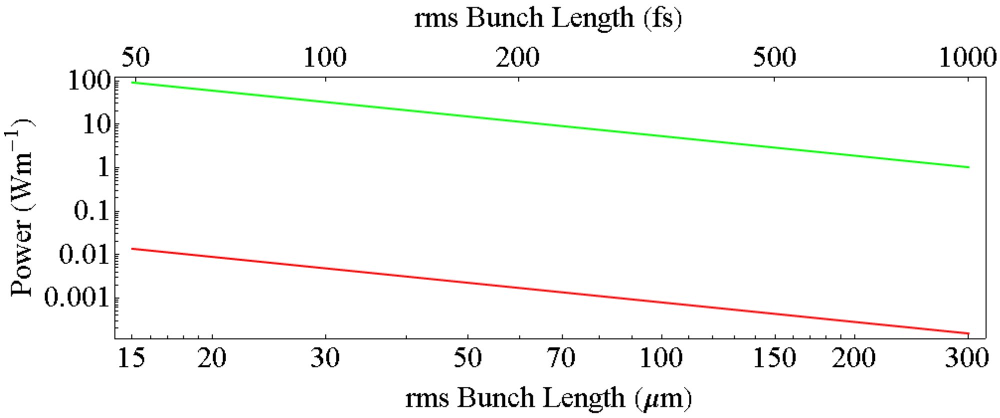

Figure 5: Power deposited per meter in a 7 mm copper vessel with an RRR of 60 operating in a 3.5T magnetic field and at 4K for the 4GLS ERL (green – 1.3 GHz, 77 pC, 100 fs) and 4GLS XUV-FEL line (red – 1 kHz, 1 nC, 250 fs).

As well as vessel heating, the energy spread growth from the c.200m 4GLS ERL transport system – which is driven mainly by the undulator vessels and the collimation system - must be limited by trading the vacuum aperture and conductivity against the local bunch length; the energy spread growth must be constrained within 0.1% to limit the spontaneous undulator output linewidth and to allow efficient driving of the included VUV-FEL [44]. This has led to the use of a progressive compression scheme [46] which gradually reduces the bunch length through the five undulator straights. Collimators are needed in the design to localise parasitic losses from beam halo, which could be considerable (c. 600 W) from the overall 4GLS average beam power of 60 MW. Wakefield estimates have been made in collaboration with TEMF Darmstadt using ECHO3D to help determine the minimum possible aperture of these collimators, and to determine how long the taper sections should be – 200 mm each end of a Cu collimator with overall length 600 mm.

Beam Break-Up is a particular issue for ERLs whereby the higher-order modes of the accelerating cavities can drive a feedback-based instability of the recirculating beam.

4GLS have produced an optimised HOM-damped 7-cell cavity design [47] and explored the role of cavity deformations and beam optics in optimising the beam break-up threshold - the latter

studied with Arc-en-Ciel, where both optics utilise graded-gradient focusing through the linac [48].

The wakefield work undertaken within the Cockcroft Institute has contributed to an understanding of the appropriate design choices for future light sources, and the expertise that has been developed with the Institute will be useful for many future light source projects.

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